L-Band Channel Modeling

Integrated CNS Technologies Conference & Workshop
Space Communications Program, NASA Glenn Research Center
1 - 3 May 2006

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Briefing Outline

- Study Objective and Motivation
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  - Simulation Context
  - Simulation Flow Charts
- Study Results
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  - Post-Processing of Simulation Outputs
  - Suggested Channel Models
- Conclusions

Study Objective and Motivation

- What we are doing
  - We are developing *small-scale* propagation models to characterize the Aeronautical Air/Ground Channel in L-Band
    - Small-scale models are essential in simulating communications system performance
    - Models will be used to estimate candidate Future Radio System (FRS) performance
- Why we are doing this
  - After an extensive literature search we concluded that little work has been done in L-band for Air/Ground communications
  - While measurements exist for terrestrial channels, no measurements currently exist for the Air/Ground channel
  - An understanding of the statistical variations of the propagation environment is fundamental to optimizing communication system performance
- What is the expected task output
  - We expect to develop representations of the L-Band aeronautical air/ground channel that characterize the fading behavior of the channel and can be used in waveform simulations of FRS candidates

Channel Modeling Background

- Propagation models are typically classified as either Large Scale Propagation Models or Small Scale Fading Models

Large Scale Propagation Models

- Propagation models that predict the mean signal strength for an arbitrary transmitter-receiver separation distance to facilitate estimation of radio coverage area and are referred to as Large Scale Propagation Models
- Characterized by a slow change in average received power with increasing distance from the transmitter. To get a sense of average received power, measurements are averaged in a local area over 10's of wavelengths
- These models are useful for link budgets and coverage analysis

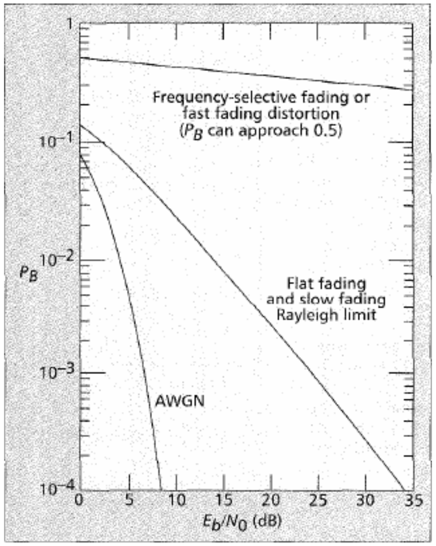
Small Scale Fading Models

- Propagation models that characterize the rapid fluctuations of the received signal strength over very short distances or short time durations are referred to as Small Scale Fading Models
- Characterized by rapid and severe changes in received signal amplitude (several orders of magnitude) with motion over very short distances.
- **These models are essential for proper waveform design and optimizing receiver implementation**

Small Scale Fading Models are the focus of this modeling effort.

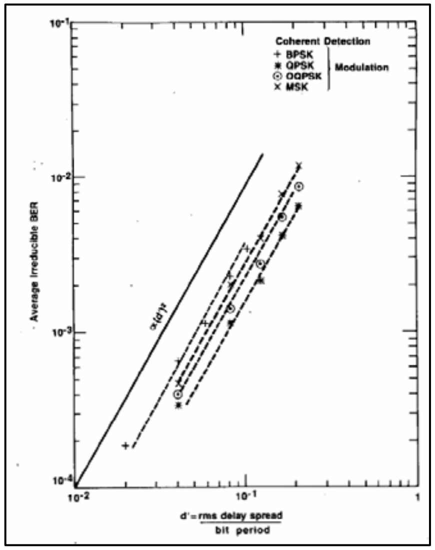
Channel Modeling Background (2)

- Small scale fading models can be classified as “frequency-selective” or “frequency-nonselective” (also called flat) fading models
  - Both flat and frequency-selective fading degrade system performance
  - Frequency-selective fading channels result in an irreducible BER
    - Mitigated by adaptive equalization, spread spectrum techniques, OFDM or insertion of pilot signals
  - Flat fading can result in destructive interference, due to the phase differences in the unresolvable multipath components
    - Mitigated by diversity and error-correction coding
  - Simply put, while large-scale models help us predict E_b/N_o, it is the channel fading characteristics that determine system performance



Error Performance

Bernard Skylar, “Rayleigh Fading Channels in Mobile Digital Communications Systems Part II: Mitigation”



Irreducible BER

Justin Chuang, “The Effects of Time Delay Spread on Portable Radio Communications Channels with Digital Modulation”

Channel Modeling Background (3)

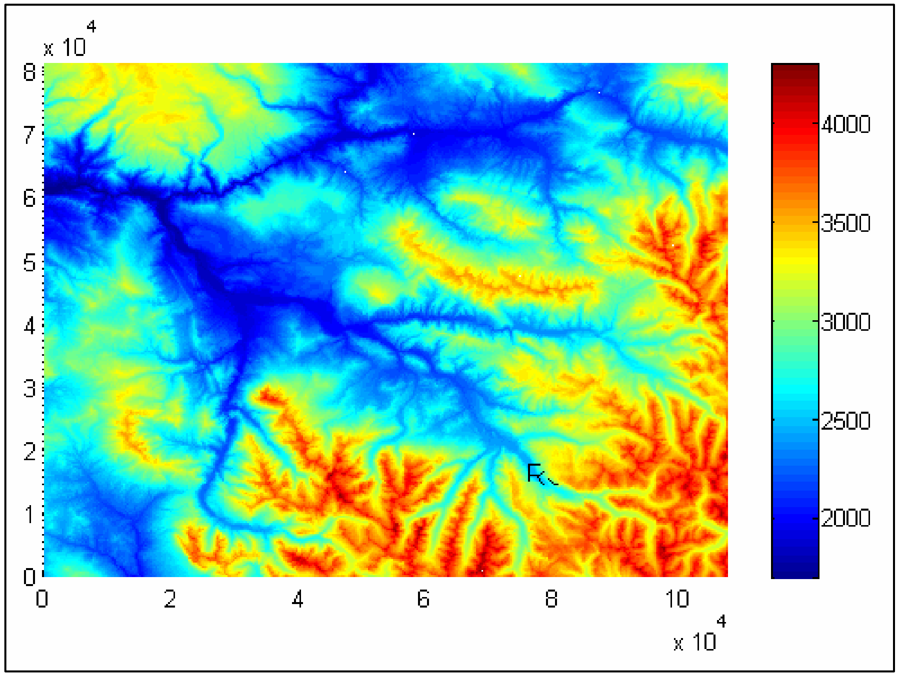
- After an extensive literature search we concluded that very little measured data exists to characterize the fading behavior of the L-band Air/Ground communications channel
- In order to have a useful model for waveform simulation and evaluation of candidate Future Radio System technologies, the following additional elements need to be estimated:
  - Delay Spread
  - Doppler Power Spectrum
  - Tap amplitudes, # of taps, fading processes, and correlation between taps
- While no measurements exist that could be used to infer these quantities directly, there is sufficient theory and analogy to be made to the body of land mobile measurements to provide a basis for estimation
  - The next section provides the details of our process to estimate the delay spread and the Doppler power spectrum parameters. The number of taps to be used in a simulation is technology dependent (given a derived excess delay spread).

Study Approach

- In order to form estimates of the delay spread and delay spread statistics, a ray-tracing simulation was developed
- The ray-tracing simulation models both diffuse and specular reflections from the Earth's surface
- Many terrain models could have been selected for this study
- Our initial approach used a flat terrain model, but after our initial investigation we concluded that mountainous terrain provides a worst-case scenario

Study Approach – Selection of Simulation Topography

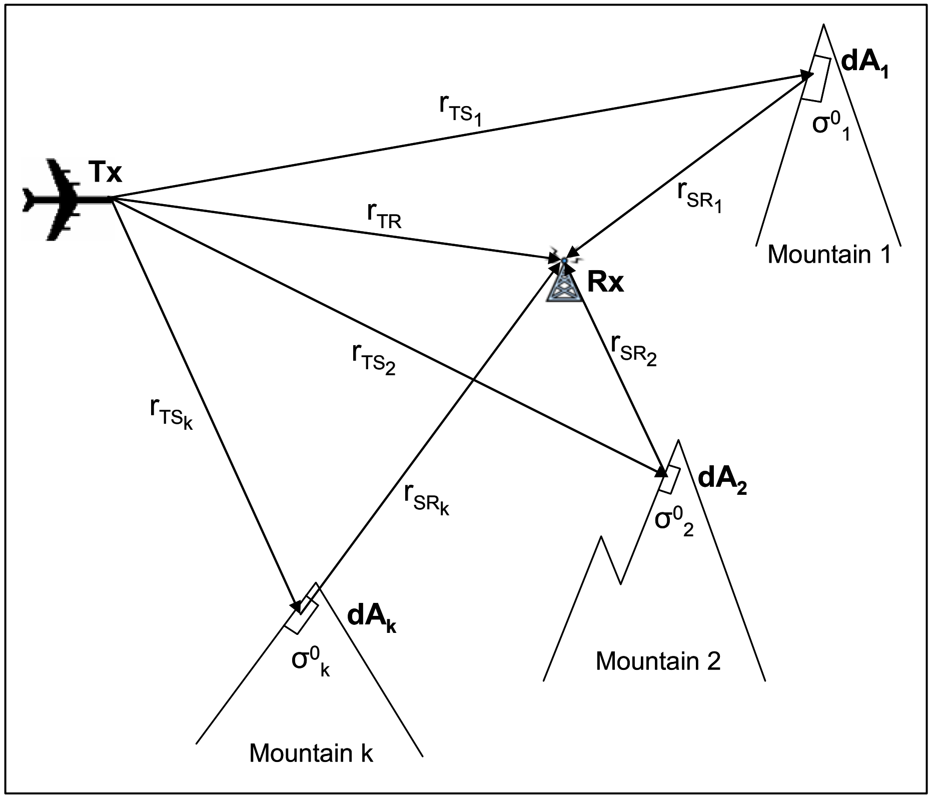
- Mountainous terrain, in the en-route case, has the potential to provide extremely long multipath delays
- Long delay spreads either limit the data rate that can be transmitted or require special techniques to achieve required performance
- In an effort to characterize a worst case scenario for multipath delay spread, we selected Aspen, CO
  - Aspen terrain and the current RCAG location are shown in the picture



Study Approach – Simulation Context

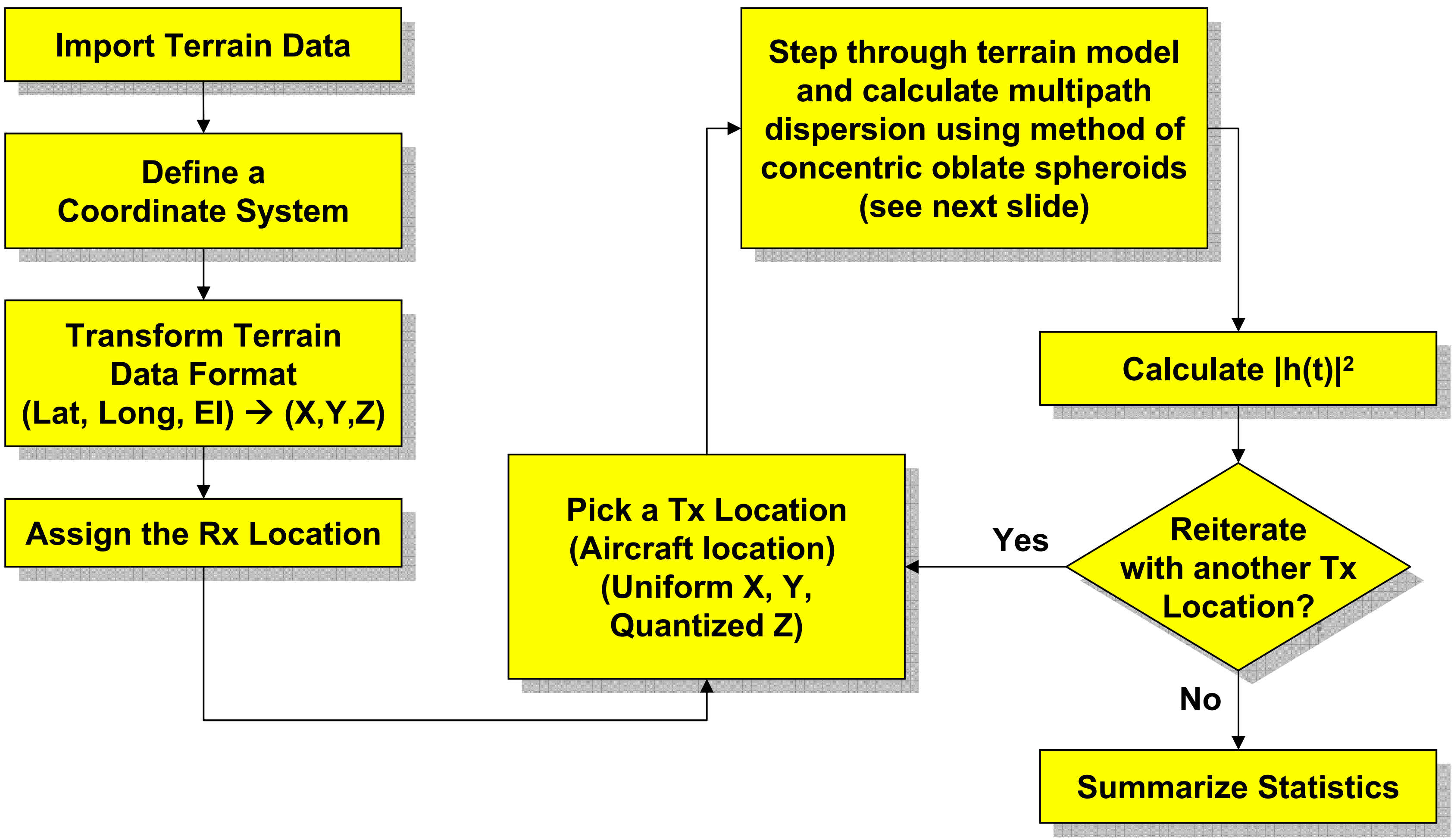
- Simulation context is shown in the picture
  - Uses bi-static radar equation and published ranges for normalized cross section in a Monte-Carlo simulation framework
- Simulation uses both Monte-Carlo and ray tracing techniques
  - Monte-Carlo elements include randomly selected aircraft position & heading (ground station is fixed) and radar cross sections
  - Ray tracing is used to calculate requisite distances
  - To identify unique multipath components, a method of concentric oblate spheroids is employed
- Although the diagram illustrates only the diffuse, both specular *and* diffuse multipath components are considered

Simulation Context Diagram



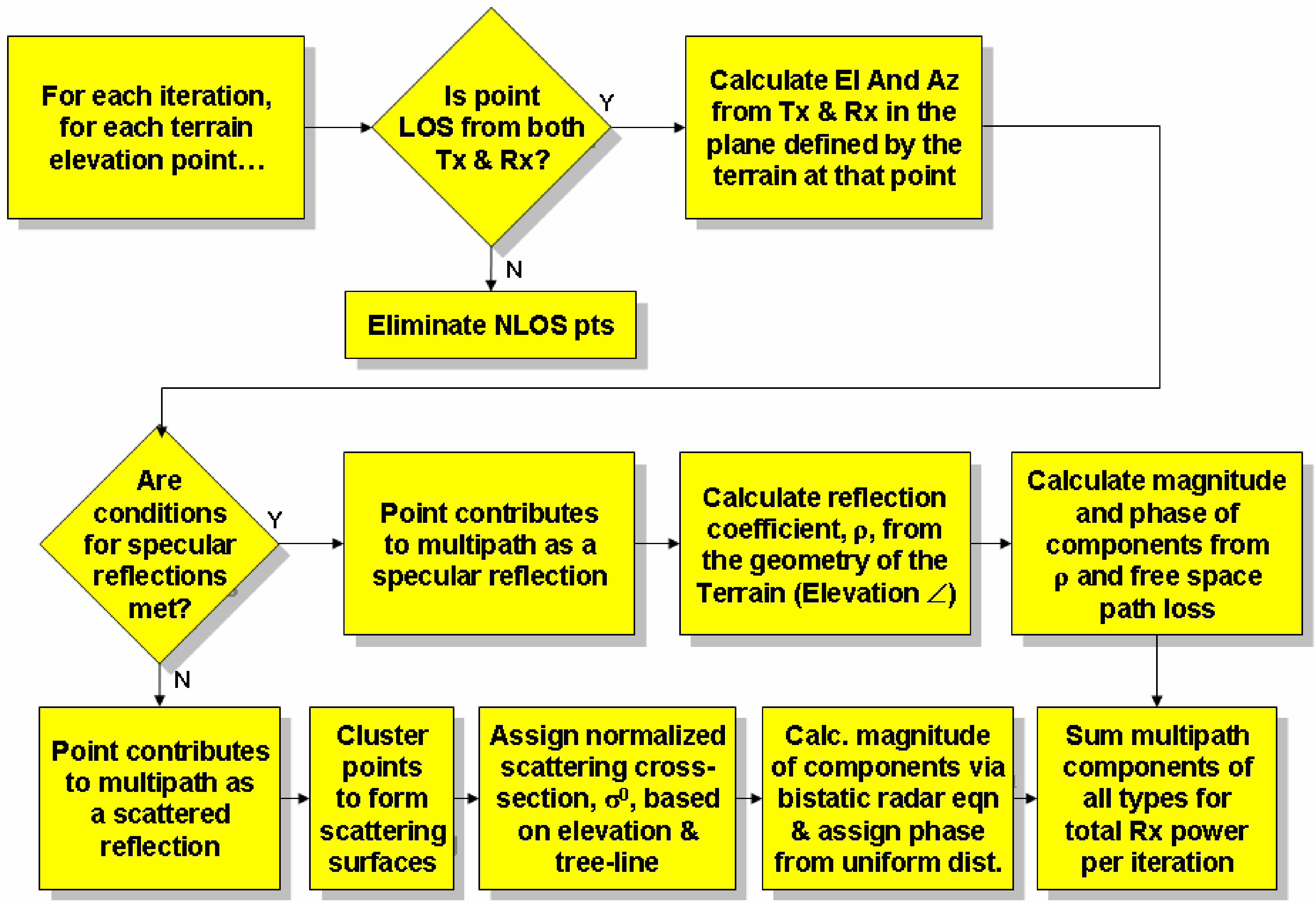
Study Approach – Simulation Flow Chart

- Flow Chart for overall simulation:



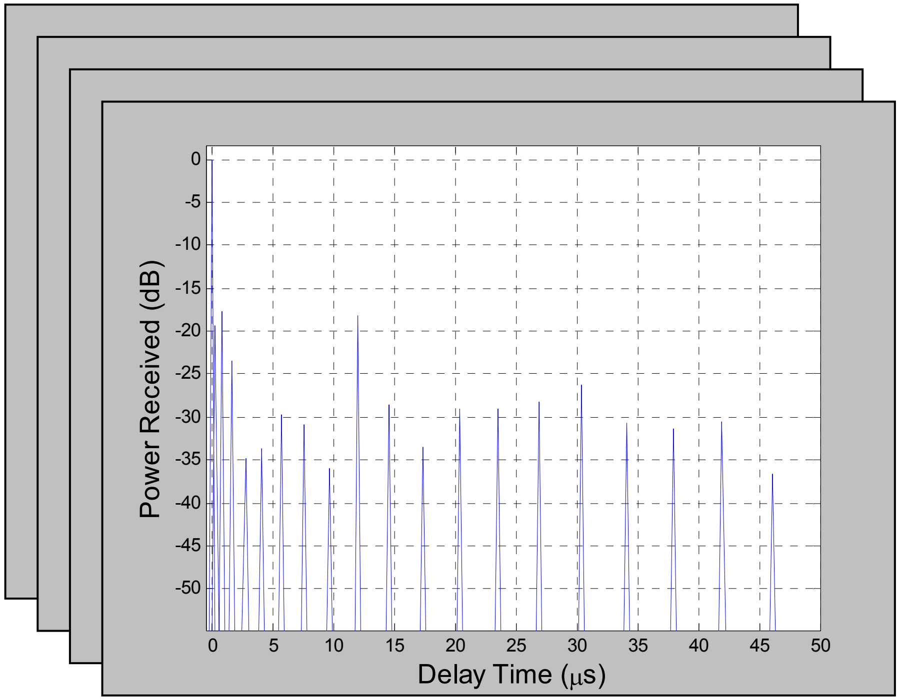
Study Approach – Terrain Analysis Flow Chart

- Flow Chart for analyzing terrain model:



Study Results – Typical Simulation Outputs

- The L-Band Channel Estimator Simulation has generated hundreds of Power Delay Profiles (PDPs)



- Data reduction techniques must be employed in order to extrapolate channel model parameters from the PDPs

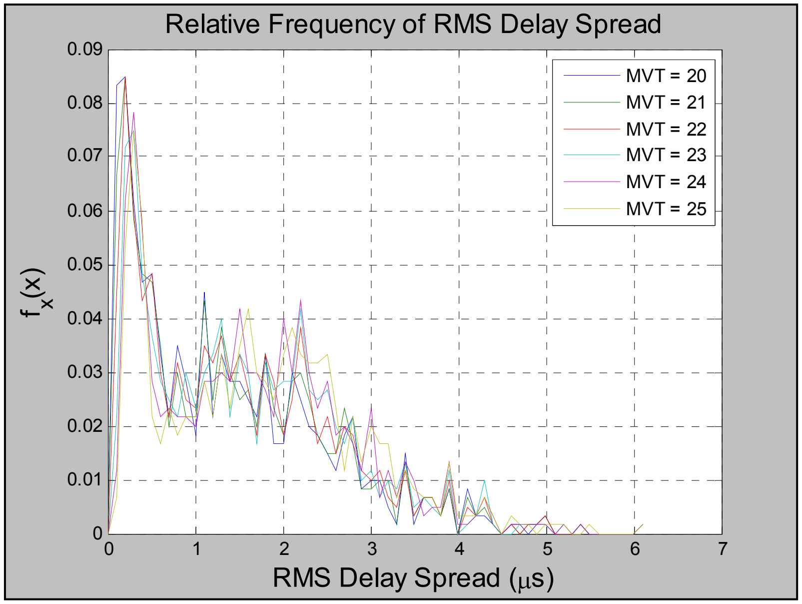
Study Results – Post-Processing of Simulation Outputs

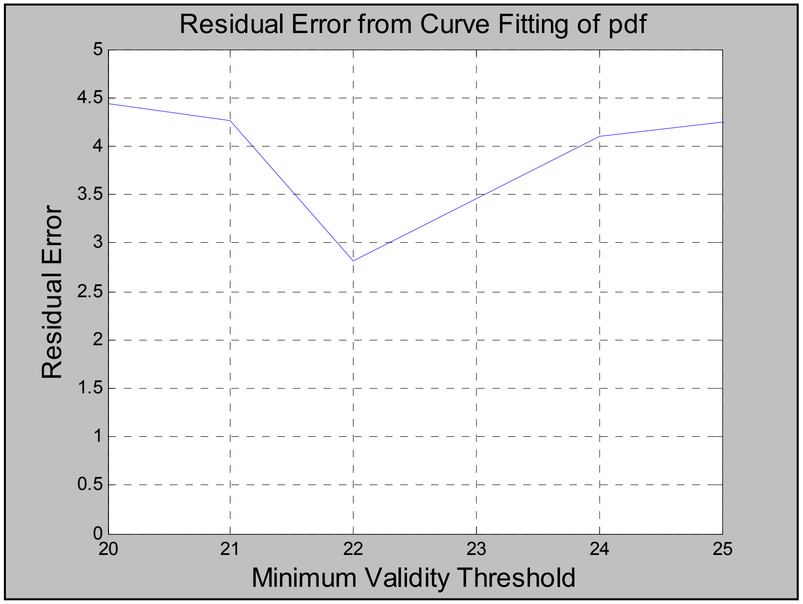
- The first step in the data reduction process is determining the Minimum Validity Threshold
  - The PDPs generated by the L-Band Channel Estimator Simulation contain multipath components that range from just a few dB to tens of dB down from the LOS component
  - If these were true measurements, many of the multipath components would not be distinguishable from the noise floor of the measurement equipment
  - The simulation differs from measurements in that it does not have a noise floor
    - For some PDPs that consist solely of very low-power multipath returns, a skewing of delay spread statistics is observed in the model
    - This behavior, while perhaps real, is not likely to be significant due to the nature of our channel (Rician)
    - In other words, although they show up in the model, these low-power returns would not degrade system performance given the presence of a strong LOS component
  - A threshold level termed the ***Minimum Validity Threshold*** (MVT) was defined to eliminate very-low power multipath returns

Study Results – Post-Processing of Simulation Outputs (2)

- Methodology for Determining the MVT
  - Start with a range of values for MVT (literature suggests 20-25 dB [Matolak])
  - Plot the relative frequency (pdf) of the RMS delay spread after applying a range of MVT values (i.e. – 20, 21, …, 25 dB) to the PDPs
  - Calculate the RMS delay spread for using each MVT
  - These pdfs are fitted to known distributions so that the statistics of the distributions represent the statistics of the channel for a particular MVT
  - Literature suggests that the pdf of RMS delay spread for a Rician channel is exponential
  - A best fit is performed for each pdf and the residual error is calculated
  - The pdfs are similar to one another, so the pdf with the least residual error (best fit) is selected

Study Results – Post-Processing of Simulation Outputs (3)





- Defining the MVT = 22 dB infers a model from which we can calculate delay spread statistics

Study Results – Suggested Channel Models

- After applying the MVT to all of the PDPs, the mean RMS-DS was calculated to be 1.4 μs

- It is instructive to consider representative technologies at this point as the technology data rate will drive model parameter estimation
  - A rule of thumb that is frequently applied is if the mean RMS-DS is at least one tenth of the symbol duration, then the channel is frequency selective (Rappaport 170)
  - Flat models differ in structure from frequency-selective models. Required simulation sampling rates also have an impact on channel model structure

Study Results – Suggested Channel Models

- In order to illustrate this, two technologies that scored well in the FCS Pre-Screening were selected for analysis: P34 and LDL

Waveform	Data Rate	Symbol Duration	1/10th of the Symbol Duration
LDL	62.5 kbps	16 µs	1.6 µs
P34	4.8 ksps*	208.3 µs	20.83 µs

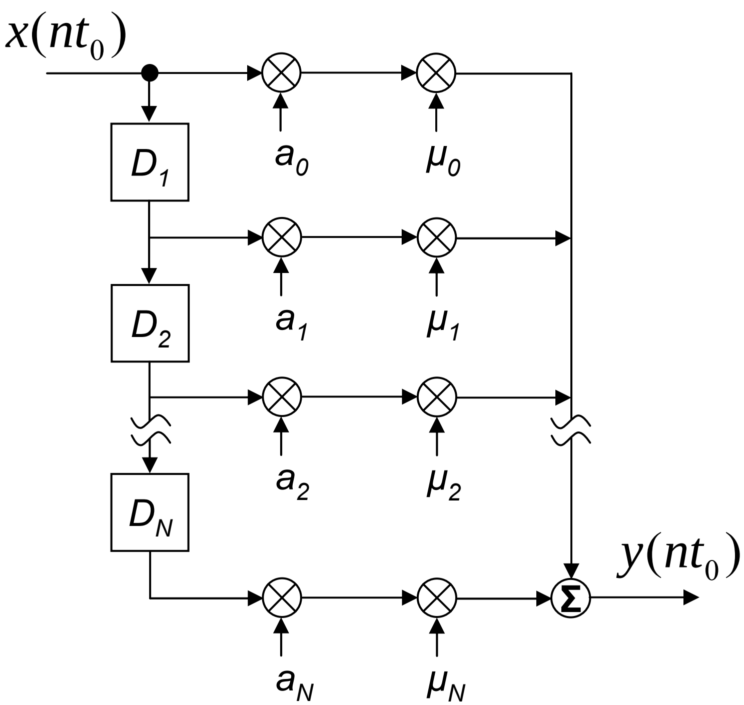
* P34 is an OFDM system. The tabulated data rate is per carrier and is the symbol rate. Overall P34 data rates range from 76.8-691.2 kbps

- Given our simulated channel mean RMS-DS,
  - P34 should undergo flat fading
  - LDL presents a borderline case because the mean RMS-DS is very close to one tenth of the symbol duration
- For this reason we have decided to develop a frequency-nonselective fading model for P34 and a frequency-selective fading model for LDL

Study Results – Suggested Channel Models (LDL)

- Channel Model for LDL:

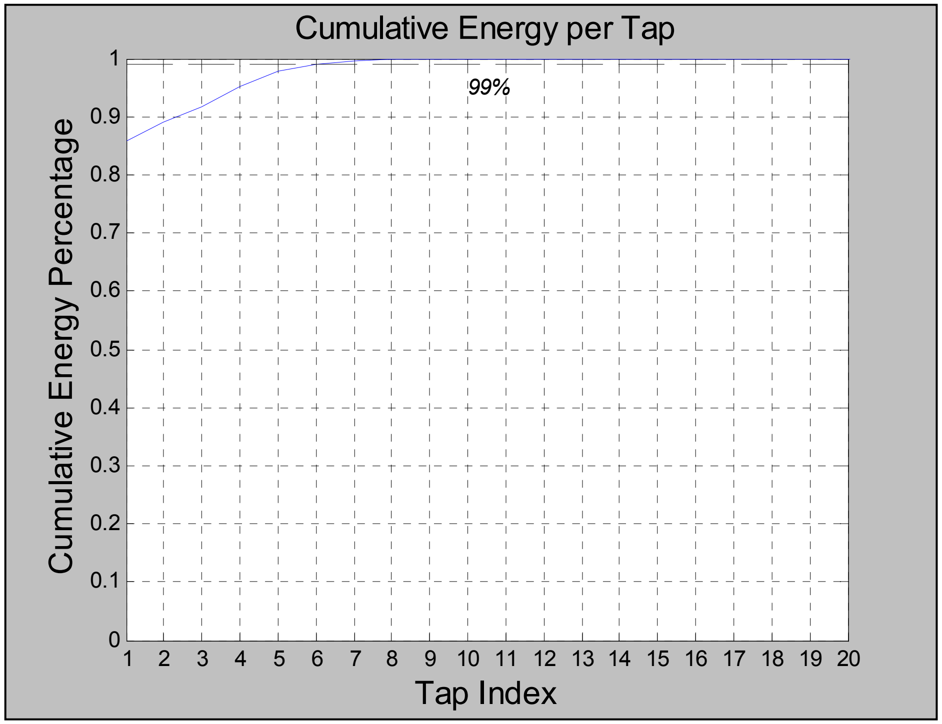
- A deterministic simulation model for a frequency-selective mobile radio channel (Pätzold 270):



- The parameters that define the LDL channel model are:
  - # of Taps (N)
  - Tap Spacing ($D_1, D_2, \ldots, D_N$)
  - Tap Weights ($a_0, a_1, \ldots, a_N$)
  - Tap Fading Processes ($\mu_0, \mu_1, \ldots, \mu_N$)
  - Other considerations:
    - Correlation between Taps

Study Results – Suggested Channel Models (LDL)

- Deriving the # of Taps
  - Each of the simulated PDPs contained a large number of multipath components
    - Some are more prominent than others on average
    - A good model would emulate the simulated channel without undue complexity
      - Should require the minimum number of taps required to achieve a "good fit"
      - Many researchers [Matolak] use the contribution of a tap to total energy as a barometer of which taps are required
      - Using this method, one selects the number of taps required to account for X% of total PDP energy
        - » We have selected X = 99% for our threshold
  - Plotting the cumulative energy per tap shows that 99% of the energy appears within the first 7 taps

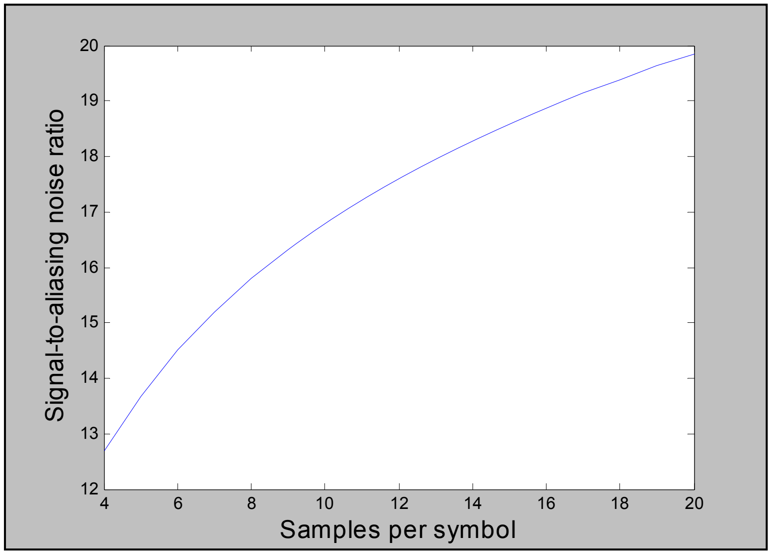


- The equation for cumulative energy through the i^{th} tap across j PDPs is:

$$CumulativeEnergy_i = \frac{\sum_{1}^{i} TapEnergy_j^i}{TotalCumulativeEnergy}$$

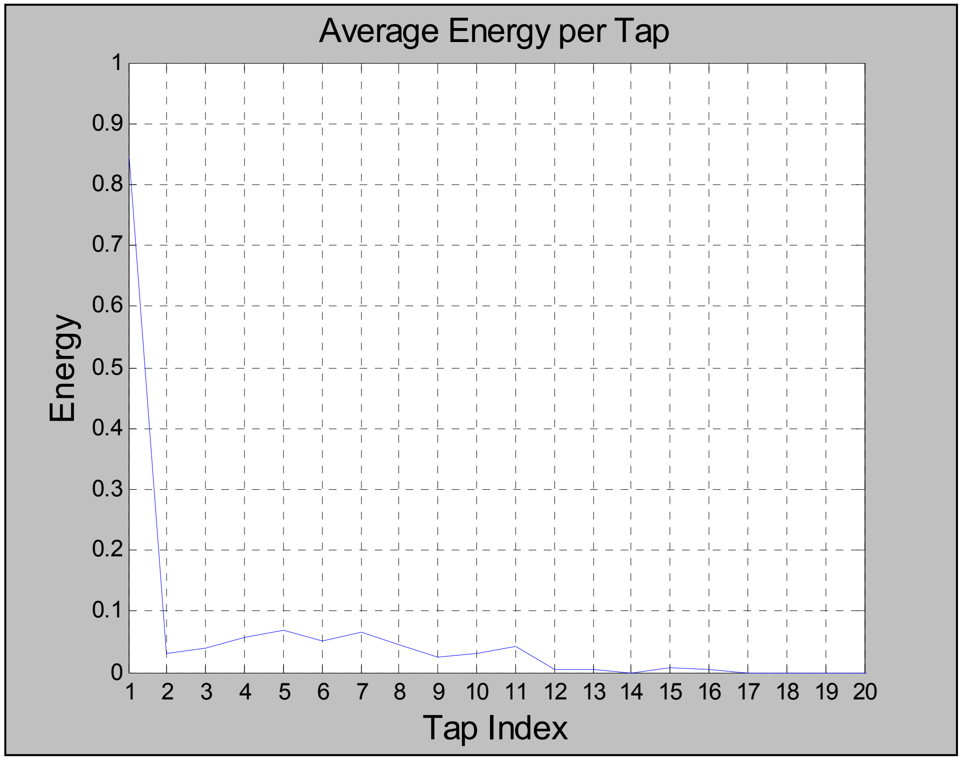
Study Results – Suggested Channel Models (LDL)

- Tap Spacing
  - The tap delays coincide with the sampling rate of the simulation they will be used in
    - Such simulations require a sampling (typically over-sampling) rate that is an integer multiple of the symbol rate
    - Aliasing concerns drive typical sampling rates to be on the order of 10 samples per symbol
  - Hence for LDL the tap spacing, t_0 = 1.6 μs (LDL symbol duration is 16 μs)



Study Results – Suggested Channel Models (LDL)

- Tap Weights
  - A plot of the average energy per tap shows the mean amplitude for each tap



- The equation for average energy for the i^{th} tap across j PDPs is:

$$AverageEnergy_i = \frac{\sum_j TapEnergy_j^i \times TapStatus_j^i}{\sum_j TapStatus_j^i}$$

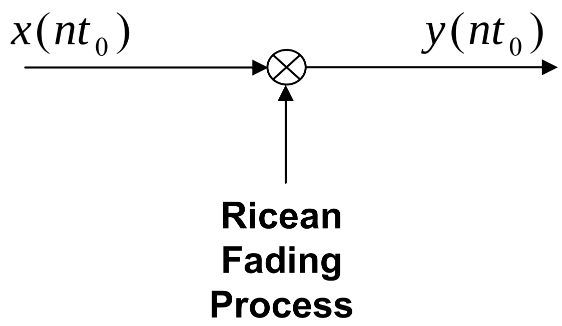
Study Results – Suggested Channel Models (LDL)

- Tap Fading Processes
  - Pdf's for each tap (#'s 1→7) were fit to known distributions with minimal RMS error so that the fading processes could be modeled
  - The table below lists the fading process, statistical mean, and variance for each of the taps:

Tap #	Delay (μs)	Power (lin)	Power (dB)	Fading Process	Doppler Category
1	0	1	0	Ricean	TBD
2	1.6	0.0359	-14.5	Rayleigh	TBD
3	3.2	0.0451	-13.5	Rayleigh	TBD
4	4.8	0.0689	-11.6	Rayleigh	TBD
5	6.4	0.0815	-10.9	Rayleigh	TBD
6	8.0	0.0594	-12.2	Rayleigh	TBD
7	9.6	0.0766	-11.2	Rayleigh	TBD

Study Results – Suggested Channel Models (P34)

- Channel Model for P34:
  - The P34 channel model is less complex than the LDL channel model because the channel is frequency-nonselective and has the form:



  - The Ricean fading process is derived in the complex baseband by creating two colored Gaussian processes
    - Rice method used to generate Gaussian Process (summation of sinusoids whose coefficients and frequencies are determined by the Doppler Power Spectrum of the channel)
  - As the process is Ricean, a time-variant mean is summed with the colored Gaussian random process
  - The magnitude of the complex-enveloped Gaussian colored processes yields the Ricean process with fade durations and amplitudes determined by the channel

Conclusions

- Conclusions
  - An RMS delay spread of 1.4 μs was predicted for a certain distance (average distance = 40 miles) from the transmitter in mountainous terrain
  - A generalized model, using methodology of Greenstein, Erceg, Yeh, & Clark, can be used to extend our model to any separation distance and has the form:

$$\overline{\sigma}_{\tau} = \overline{\sigma}_{\tau_0} d^{\varepsilon} A$$

- where,
  - d is the distance in km
  - $\sigma_{\tau 0}$ is the median value of the RMS delay spread at d = 1 km
  - ε is an exponent that lies between 0.5-1.0, based on the terrain type
  - A is a lognormal variate

  - Further work required to characterize σ, ε, and A; however the simulation and methodology clearly accommodates this